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Strength of brickwork and blockwork walls : design for vertical load

The Code of Practice for the structural use of masonry, BS 5628 : Part 1 : 1978, deals with unreinforced masonry assembled from bricks or blocks mortared together; it is written in terms of limit state design and is intended to supersede CP 111 which used the permissible stress concept. Other important differences are the inclusion of sections dealing with laterally loaded masonry and design for accidental damage.

BS 5628 has been written for use by chartered structural and civil engineers or other appropriately qualified persons. This digest gives some background to the main recommendations in respect of the vertical loading and replaces Digest 61 which is now withdrawn. The design of concrete walls is covered by CP 110.

Design approach

The basis of limit state design is that the designer should consider all the likely ways in which a structure or element could fail to perform its required function and should then design against such failures. The design must take into account therefore the factors conferring stability to the whole of a masonry structure, even though the detailed approach is to break the structure down into walls and other elements partially or totally bounded by lateral supports and to design each element so that there is a reasonable margin of safety against the ultimate limit state (collapse) being reached. Using BS 5628, the designer must determine, either intuitively or by calculation, whether the critical design condition for any wall is compressive, shear (in or out of plane), tensile or flexural (in or out of plane), (Fig 1). The wall is then designed to meet the assumed critical load condition, and checked for the assumed non-critical conditions. The criterion on which a wall is adjudged to be satisfactory or not is the relationship:

Design resistance $\geqslant$ design load.

Design for vertical load

Calculation of the design strength and load is based on characteristic values and a partial safety factor format in which the following concepts are required:

Characteristic compressive strength f_k: the ultimate compressive strength of brickwork as measured in the laboratory and taking into account laboratory sample to sample variability.

Characteristic load S_k: the weight of the finished construction in the case of dead load, or a statistical estimation of the likely load in the case of loads due to occupancy, snow or wind. In practice the loads will be obtained from CP3 Ch V or by calculation using BS 648.

Materials partial safety factor, γ_m: a number by which the characteristic strength is divided to allow for the possible difference in quality of materials and workmanship between laboratory test walls and a wall on site.

Load partial safety factor, γ_f: a factor by which the characteristic load is increased to allow for uncertainty in the data on which it is based, eg the variability of the actual density of materials, the uncertainty of wind data and snow data, beyond those considered in deriving the characteristic values.

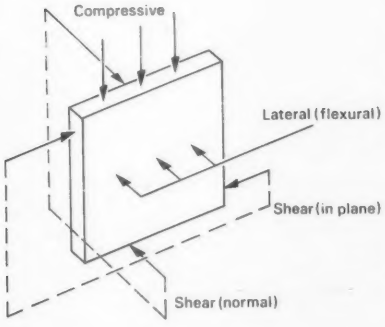

Fig 1 Different loadings on a wall

Prepared at Building Research Station, Garston, Watford, WD2 7JR
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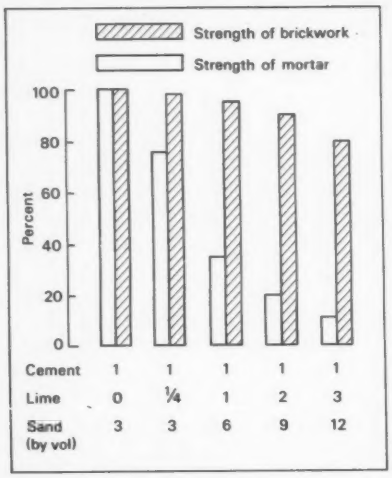


Fig 2 Effects of mortar mix proportions on the crushing strengths of mortar and brickwork built with medium-strength bricks. Strengths are shown relative to the strength of a 1:3 cement-sand mortar and the brickwork built with it.

For the simple, vertical load case (axially loaded squat solid wall):

$$\text{Design resistance} = \frac{\text{Characteristic strength } (f_k)}{\text{Materials partial safety factor } (\gamma_m)} \times \text{area (Length x thickness)}$$

Design Load = Characteristic load x load partial safety factor

BS 5628 gives values of f_k for common materials and values of γ_m which allow for the difference between laboratory and site-constructed masonry. A range of values is suggested depending on the degree of quality control in the manufacturing and construction processes. It also lists γ_f for various combinations of dead, imposed and wind load. The magnitudes of the various partial factors have been chosen to reflect explicitly the relative likelihood of extreme values of load and strength. In combination they correspond broadly to the overall factor of safety implicit in the permissible stress approach of CP 111 but offer the flexibility to consider individual areas of uncertainty.

Further considerations must be taken into account when designing slender walls, walls stiffened by piers, eccentrically loaded walls, cavity walls, walls with complex plan shapes and walls subject to concentrated loads or to significant lateral or shear forces.

BS 5628 gives characteristic strengths of brick and block masonry; guidance is also given on the values appropriate to other types of masonry, such as hollow blockwork filled with concrete, dressed natural stone and random rubble walls. The design stresses can be derived by dividing these values by the appropriate material safety factor γ_m, and the load capacity of an axially loaded squat wall can be calculated using the equation given above. In domestic buildings, where lower strength materials may be used in narrow walls between large openings in the front and rear elevations, wall thickness may be governed only by vertical stresses. However, more frequently the critical requirement will be the design for lateral load.

Strength relationships between walls and mortars

The underlying data and relationships in BS 5628 are the same as in CP 111. Generally, the maximum strength of brickwork is obtained with mortar mix proportions of (cement and lime) to sand of 1:3 by volume. There is however, little advantage in using a very strong cement-sand mortar in most brickwork and blockwork walls. Digest 160 discusses the factors, in addition to strength, which affect the choice of mortars.

Figure 2 compares the strengths of mortar and brickwork for a number of mortar mixes when a medium-strength brick is used. The mortar loses strength as the proportion of lime in the mortar is increased, although the effect on the brickwork is not nearly so marked.

For brickwork with high-strength bricks, the fall in strength of the brickwork is much more pronounced as progressively weaker mortars are used. Thus, in order to utilise the full capacity of high-strength bricks (70 N/mm² or more), a 1:3 cement-sand mix is needed. For lower strength bricks or blocks, mortars with an increased proportion of lime can be used without any great loss in masonry strength (Table 1).

For walls loaded vertically, BS 5628 also recognises correctly proportioned mortars based on masonry cement mixes, and aerated cement-sand mixes, as equivalent to the weaker cement-lime-sand mixes.

Table 1 Suitable mortar mixes for various unit strengths

Unit strength (N/mm²)	Mortar mix (by vol)	Designation in BS 5628
10	1:2:9	(iv)
20-35	1:1:6	(iii)
48-62	1:¼:3	(ii)
70 or more	1:0:3	(i)

Note: The weaker cement-lime-sand mixes may be replaced by masonry cement-sand or plasticised cement-sand mixes of equivalent strength.

Strength relationships between walls and building units

The relationships in BS 5628 between strengths of masonry, structural unit and mortar are essentially similar to those on which CP 111 is based although detailed changes have been made in the light of more test results, particularly on high-strength brickwork and low-strength blockwork.

Strength relationships are shown in Fig 3; the walls were tested in the air-dry condition but the crushing strengths of the units were taken as the wet strengths, as required by the British Standards dealing with testing building units, ie BS 187, 3921 and 6073.

Brickwork

The strength ratio for brickwork:brick varies from slightly less than half to slightly less than one-fifth, the latter being sometimes found for high-strength (Class A) bricks used with a weak mortar. The trends indicated in Figs 2 and 3 are of particular importance for brickwork designed to BS 5628. In the Code, the characteristic compressive strengths of walls made of various bricks and mortar mixes are based on relationships of this kind, taking variability into account. The actual values of f_k allowed by the Code for brick-shaped units are given in Table 2. They represent the ultimate strengths of brickwork and generally are about 4.5 times the basic stresses given in CP 111.

Blockwork

Loading tests on one-block thick walls built with low to medium strength blocks of normal proportions (ie height exceeding thickness by a factor of two or more) give ratios of wall strength to block strength of between 0.5 and 1. This apparent enhancement in relation to 'brick-shaped' units (height less than thickness) occurs because the crushing strength test under-estimates the strength of the more slender block-shaped units when tested in isolation; there is, however, limited effect on the strength of the wall which has the same slenderness ratio for brick or block-shaped units. This apparent enhancement does not apply to the higher strength hollow or cellular units which behave much as bricks. The characteristic strength values given in Table 2 reflect these trends by incorporating ratios of characteristic strength of walls to block strength in the range one to one-fifth as appropriate. Other tables are given for squat form blocks when ratio of height to least horizontal dimension is 0.6 and for hollow blocks. For the purposes of the Code, cellular blocks should be

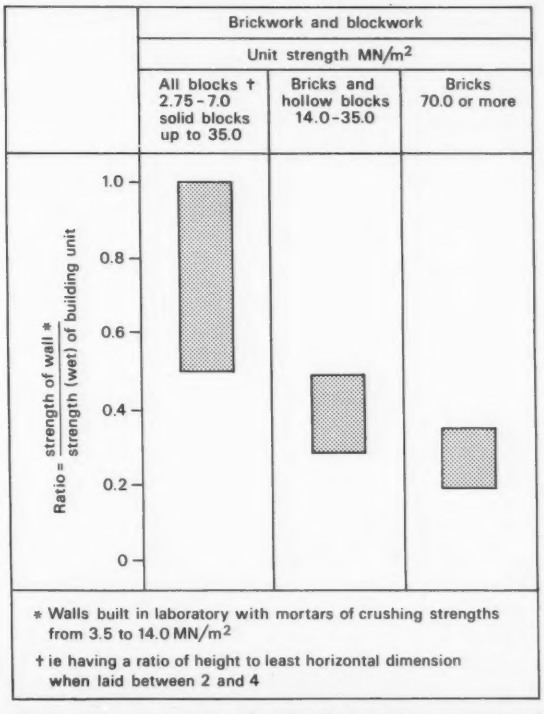

Brickwork and blockwork
Unit strength MN/m²
All blocks † 2.75 - 7.0 solid blocks up to 35.0
Bricks and hollow blocks 14.0 - 35.0
Bricks 70.0 or more
Ratio = strength of wall * / strength (wet) of building unit
1.0
0.8
0.6
0.4
0.2
0
* Walls built in laboratory with mortars of crushing strengths from 3.5 to 14.0 MN/m²
† ie having a ratio of height to least horizontal dimension when laid between 2 and 4

Fig 3 Ratio of strength of storey-high wall to strength of building unit (block, brick or cube specimen)

Table 2 Characteristic compressive strength of masonry, f_k

Constructed with standard format bricks

Mortar Designation	Compressive strength of unit *(N/mm²)*								
	5	10	15	20	27.5	35	50	70	100
(i)	2.5	4.4	6.0	7.4	9.2	11.4	15.0	19.2	24.0
(ii)	2.5	4.2	5.3	6.4	7.9	9.4	12.2	15.1	18.3
(iii)	2.5	4.1	5.0	5.8	7.1	8.5	10.6	13.1	15.5
(iv)	2.2	3.5	4.4	5.2	6.2	7.3	9.0	10.8	12.6

Constructed from solid concrete blocks having a ratio of height to least horizontal dimension of between 2.0 and 4.0

Mortar designation	Compressive strength of unit *(N/mm²)*							
	2.8	3.5	5.0	7.0	10	15	20	35 or greater
(i)	2.8	3.5	5.0	6.8	8.8	12.0	14.8	22.8
(ii)	2.8	3.5	5.0	6.4	8.4	10.6	12.8	18.8
(iii)	2.8	3.5	5.0	6.4	8.2	10.0	11.6	17.0
(iv)	2.8	3.5	4.4	5.6	7.0	8.8	10.4	14.6

treated as hollow blocks. The tables in BS 5628 avoid the need to apply separate factors to allow for the shape of the units as required in CP 111. Interpolation between values given in Table 2 is allowed and is facilitated by graphs corresponding to each subtable.

Slenderness ratio

Brickwork and blockwork walls of a given thickness and material strength tend to fail at lower loads as their height increases. This is caused primarily by elastic instability, ie a tendency to buckle, initiated by differences of the stiffness from one side of the wall to the other due to variations of materials and workmanship. In design, therefore, the slenderness is important; for most purposes, it is defined as the ratio of effective height to effective thickness. These 'effective dimensions' are used to take into account other features that affect the behaviour and load-bearing capacity of the member.

BS 5628 recommends, as in CP 111, that for walls set in Portland cement mortars, the slenderness ratio should not exceed 20 for walls less than 90 mm thick in buildings of more than two storeys, and 27 in all other cases. The design strengths of walls having slenderness ratios in excess of 8 are reduced on a sliding scale up to the maximum permitted slenderness ratio of 27, Column 1 of Table 3.

Table 3 Capacity reduction factor, ß

Slenderness ratio h_{ef}/t_{ef}	Eccentricity at top of wall			
	Up to 0.05*t* *(see note 1)*	0.1*t*	0.2*t*	0.3*t*
0	1.00	0.88	0.66	0.44
6	1.00	0.88	0.66	0.44
8	1.00	0.88	0.66	0.44
10	0.97	0.88	0.66	0.44
12	0.93	0.87	0.66	0.44
14	0.89	0.83	0.66	0.44
16	0.83	0.77	0.64	0.44
18	0.77	0.70	0.57	0.44
20	0.70	0.64	0.51	0.37
22	0.62	0.56	0.43	0.30
24	0.53	0.47	0.34	
26	0.45	0.38		
27	0.40	0.33		

Note 1. It is not necessary to consider the effects of eccentricities up to and including 0.05_t.

Note 2. Linear interpolation between eccentricities and slenderness ratios is permitted.

Effective height and lateral support

The effective height is related to the support provided to restrict lateral movement in the member. Rules governing the effective height to be assumed under various conditions of support are set out in BS 5628. For example, for a simple column member supported top and bottom, the effective height is the actual height between the lateral supports. For columns supported only at the bottom, an effective height of twice the actual height must be used. Walls are similarly regarded but it is accepted that the factors responsible for loss of strength with increasing slender-

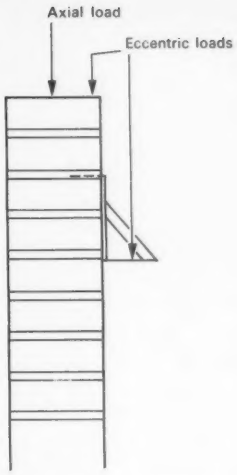


Fig 4 Axial and eccentric loads

ness are less serious for walls than columns. A distinction is also made in the effective heights to take account of the lateral support provided by different forms of floor or roof system at the boundaries of the wall. In normal domestic dwellings of up to three storeys, it is not necessary to use straps in cases where timber or concrete floors have a reasonable bearing (greater than 90 mm) on the loadbearing wall and these structures are deemed to provide enhanced resistance to lateral movement of a member. In cases where joist hangers are used instead (eg on party-walls to reduce sound transmission), straps must be used and the resultant connection is deemed to provide only simple resistance against lateral movement.

Where walls are bounded by lateral supports giving only simple resistance to lateral movement, the effective height is taken to be the actual height; where enhanced resistance is provided, the effective height is reduced to 0.75 of the actual height.

Where floors and roofs span parallel to a wall it is essential to provide straps or ties if the floor is to act as a lateral support. Where straps are not used the walls should be designed on the assumption that the horizontal support is not present.

Appendix C of BS 5628 lists a range of connections which will provide simple resistance to lateral movement, although in housing up to three storeys some connections may afford enhanced resistance.

Effective thickness

Normally the effective thickness assumed for calculating the slenderness ratio is the actual thickness of the member but there are two exceptions:

(a) A loadbearing wall bonded into piers or intersecting walls. The wall is stiffened by the additional features and an allowance for this is made by taking an effective thickness greater than the actual thickness. With suitably spaced and sized piers, an effective thickness can be used of up to a maximum of twice the actual thickness. However, where a loadbearing pier is bonded into adjacent walling, any beneficial interaction is usually small so that no increase in the effective pier dimension can be assumed. In such cases it is preferable to assume that the load is applied centrally on the pier and to ignore the presence of the walling.

(b) A cavity wall, as discussed later.

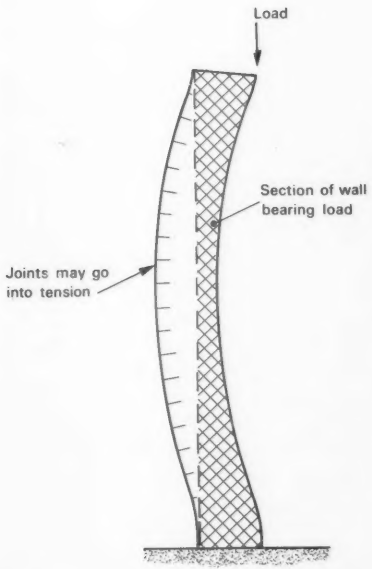


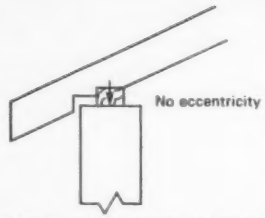
Fig 5 Exaggerated effect of eccentric load

Effective length

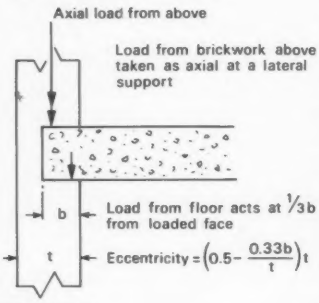
As an alternative in walls where there are frequent piers or bonded intersecting walls, the slenderness ratio of a loadbearing wall can be based on an effective length between vertical supports (ie return walls and piers, into which the wall is bonded) instead of an effective height. This design method is based on the assumption that instability due to the normal form of buckling will be prevented by the vertical supports. When this concept is used the designer must carefully consider the adequacy of these lateral supports for the particular wall. In many practical cases vertical support in the form of piers could not be considered to have sufficient stiffness to allow the loadbearing wall to be carried to any height. Rules for determining the value of effective length are similar to that of height, ie length x 1.0 for simple lateral support and length x 0.75 for enhanced support; values for walls having one free edge are, respectively, length x 2.5 and length x 2.

Eccentricity and effect of eccentric loading

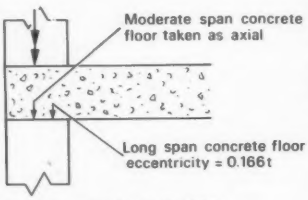
Eccentricity of vertical loading arises where the line of action of the load on a wall is not in the centre of the wall (Fig 4). In Table 3, which reproduces Table 7 from BS 5628, it is expressed as a fraction of the wall thickness. The effect is to cause the side of the wall on which the load is acting to suffer a greater compressive shortening than the other side, which can, under certain combinations of load and eccentricity, go into



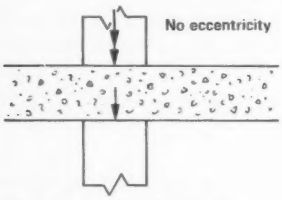
(a) load applied via centred wall plate


Axial load from above
Load from brickwork above taken as axial at a lateral support
b
Load from floor acts at 1/3b from loaded face
t
Eccentricity = (0.5 − 0.33b/t)t

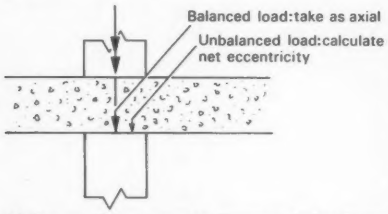
(b) generalised case



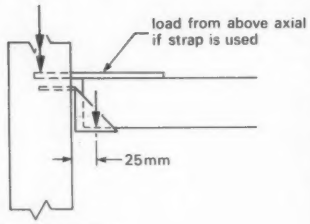
(c) Concrete floor spanning full width



(d) Continous floor load axial



(e) Non continous concrete floors or timber floors spanning from both sides



(f) Corbel or joist hanger

Fig 6 Assessment of eccentricity

tension. Since walls of brickwork and blockwork have a low tensile strength they are particularly sensitive to eccentric loads. Table 3 illustrates the reduction in usable strength that occurs as a result of increasing the eccentricity of the load, according to the theoretical method used in BS 5628. In this method, assumptions about the distribution of eccentricity in a loaded wall are combined with a rectangular stress block to derive capacity reduction factors. When applied to characteristic strengths they give directly the load capacity of walls or columns without the need for intermediate calculation as in CP 111. Even for squat walls the capacity of the wall will be reduced because the effective cross section of brickwork bearing the load (the working thickness) is reduced, Fig 5. As the slenderness ratio increases the combined effect of slenderness and eccentricity reduces the stability of the wall and further reductions in design capacity are required to maintain safety. Table 3 gives the capacity reduction factor for the range of eccentricities and slenderness ratios which have been checked by experiment. Eccentricities of up to 1/20th (0.05) of the thickness of the wall may be disregarded as they are included in the value of ß in Table 3. Use of eccentricities or slenderness ratios outside the values in Table 3 are not considered wise. Although values for the capacity reduction could be calculated using Appendix B of the Code they are likely to be too small to be of value in design.

For axially loaded walls BS 5628 gives load capacities similar to CP 111 but for eccentrically loaded walls the capacity is enhanced, often considerably. It should be emphasised that the margins of safety for slender walls with highly eccentric loads are especially likely to be reduced where the workmanship is poor and that in these circumstances the supervision of the work is particularly important. It should also be noted that because 'capacity reduction factors' for very eccentric loads are numerically small walls designed for such loads may be uneconomic.

Assessment of eccentricity

The assessment of eccentricity of vertical loading at a particular junction eg between a wall and a floor, in a brickwork or blockwork wall is made complex by the many possible combinations of wall and floor systems. The structural behaviour of the junction will be affected by the magnitude of the loads, the rigidity of the inter-connected members and the geometry of the junction. It is seldom possible to determine the eccentricity of load at a junction by calculation alone, and the designer's experience must be his guide. Some help in assessing the eccentricity of loading on walls in domestic constructions is given below.

The primary assumption is that the load transmitted to a wall by a single floor or roof acts at one-third of the depth of the bearing area from the loaded face of the wall or loadbearing leaf (Fig 6b). Thus, in cases where concrete floors bear over the full width of the wall (Fig 6c), the centre of action should normally be taken as $^1/_6$ of the thickness of the wall from the centre in the direction of the load. However, in cases where the floor or roof is of very short span or very stiff, or if the load is applied via a centred wall plate (Fig 6a), it may be reasonable to regard the load as axial. In cases where a continuous stiff (eg concrete) floor spans over a wall (Fig 6d) the load can be considered to be axial provided the loads and spans on each side are not greatly different. In similar structures with more flexible floors or roofs, or structures where independent floors or roofs span on to each side of a wall, the load may be assumed to be axial provided that the span of the floor or roof on one side does not exceed the other by more than about 50 per cent. In cases where the difference is greater or two different types of floor are used, the net eccentricity should be assessed using the 'one-third of bearing area' rule (Fig 6e).

For a wall corbelled out to support a floor or roof, or where metal joist hangers are used, the load may be assumed to act at a distance of 25mm from the face of the wall, as in Fig 6f.

The other important assumption in the Code is that all vertical loads

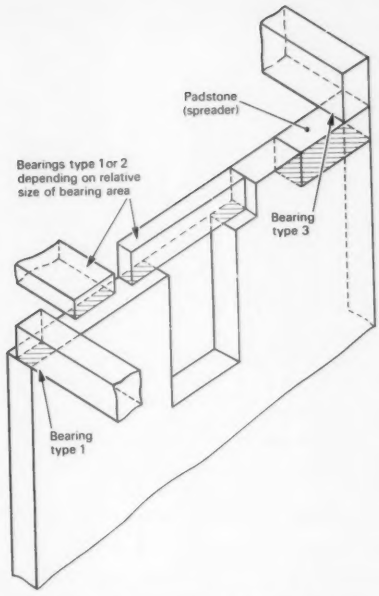


Fig 7 Where concentrated load should be taken into account - loaded areas hatched.

transmitted from above a lateral support act axially. Thus, in assessing the resultant eccentricity at a wall/floor junction in a multi-storey building, the loads transmitted to walls from the structure above by axially aligned masonry walls may be assumed to be axial.

Concentrated loading

Where floors or roofs are supported without interruption along the whole length of a wall, it is assumed that the load is uniformly distributed on the wall. Although not strictly in this category, floor and roof joists, filler joists and ribs of hollow tile floors are regarded similarly.

In practice, design calculations for loadbearing walls must also be capable of dealing with concentrated loads imposed, for example, by roof trusses, spine beams or lintels, in order to prevent failure from crushing or splitting under localised loading. Typical cases are shown in Fig 7.

It is well known that allowable bearing stresses for concentrated loads can safely exceed the design stress allowed for uniformly distributed loading. This is because of both the strengthening effect provided by the lateral restraint of material directly under the local load, and the distribution of the load throughout the depth of the wall.

The new guidance is much more detailed than in CP 111. In BS 5628 there are three types of concentrated load application. For detailed guidance users should consult the Code but briefly the types are:

Type 1 Concentrated loads from floors, lintels etc bearing over substantial areas of the loaded wall where stresses may be up to 1.25 times the normal design stress.

Type 2 Concentrated loads from floors, lintels etc bearing over very limited areas of the loaded wall where stresses may be up to 1.5 times the normal design stress.

Type 3 The special case of a concentrated load borne by a properly designed spreader or pad located at the end of a wall where stresses may be up to twice the normal design stress.

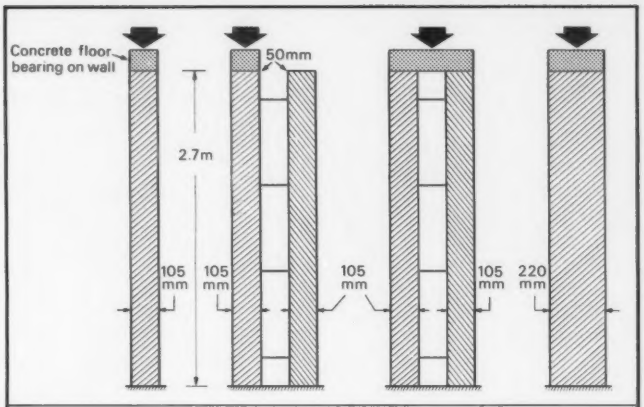
It should be emphasised that all other loading on the same area as the concentrated load must also be taken into account in the design.

Occasionally, concentrated loads cause high local stresses and for very weak solid and some hollow brick or block walls it may be necessary to increase bearing areas or to use padstones or spreaders. The latter may also be needed for any type of wall where indeterminate but very high local stresses occur, eg at the outer edge of a wall supporting a cantilever.

Cavity walls

The most common loading case for cavity walls is where only the inner leaf acts as the loadbearing leaf. In this case only the cross section of the loadbearing leaf may be used for supporting the load from above. It is reasonable however to accept that the stiffening and propping action of the other leaf is taken into account and this is done by adjusting the effective thickness; this is taken to be two-thirds of the combined thickness of the two leaves or the actual thickness of the loaded leaf, whichever is the greater. Since for most cavity walls with two 100 mm leaves the effective thickness $= \frac{2(100 + 100)}{3} = 133$ mm, the slenderness ratio will be reduced pro rata and the 'capacity reduction factor' will be increased accordingly in comparison with a 100 mm single leaf wall.

A comparison of wall strengths is given in Fig 8. It will be noted that the strength of 260 mm cavity construction with both leaves loaded is 16 per cent less than that of the 220 mm thick solid wall. When the load is carried concentrically on one leaf only, the cavity construction is 22 per cent stronger than a loaded leaf standing alone, because of the stiffening provided by the other leaf tied to it.



Slenderness ratio	19.3	14.5	14.5	9.2
Capacity reduction factor	0.72	0.88	0.88	1.0
Relative strength	1.0 * 0.39 *	1.22 * 0.48 *	2.13 0.84	2.53 1.0

* these values include the 1.15 enhancement factor for narrow walls

Fig 8 Design strengths of solid and cavity brickwork walls

Wall ties are intended to share lateral forces and deflections between the two leaves. BS 5628 allows cavities of between 50 and 150 mm and specifies the spacing and type of ties suitable for the different widths. It should be emphasised that butterfly ties are not, under any circumstances, suitable for cavities wider than 75 mm because their axial compressive strength and stiffness are not great enough to ensure proper transfer of any lateral force; also they should not be used in walls above two storeys in height. Double triangle and vertical twist ties may be used in circumstances where butterfly ties are unsuitable and some designs of plastic tie may also be a suitable alternative.

Further reading

British Standards

BS 187:1978 Specification for calcium silicate (sandlime and flintlime) bricks
BS 648:1964 Schedule of weights of building materials
BS 3921:1974 Clay bricks and blocks
BS 5628 Code of practice for the structural use of masonry.
Part 1:1978 Unreinforced masonry
BS 6073 Precast concrete masonry units.
BS CP3 Code of basic data for the design of buildings Chapter V Loading

BRE Digest

160 Mortars for bricklaying

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